Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

THE PROBLEMS OF GEOLOGY.[1]

THE subject "The Problems of Geology" was assigned to me. I should not have ventured to select so formidable a topic for a brief address.

RELATIONS OF THE SCIENCES.

We are all aware that geology is a many-sided subject. While at the outset it was a simple observational study, it soon developed physical, chemical, astronomical, and biological sides. The importance of these different sides has continuously increased, so that we now often speak of physical geology, chemical geology, astronomical geology, and biological geology.

To appreciate the position of geology among the sciences it is necessary to go back to fundamental definitions. Natural philosophy in the old and broad sense may be defined as the science which treats of energy and matter. But investigations have shown that the ether also must be considered, and hence this definition needs modification. Some physicists have been inclined to extend the scope of the term "matter" to include matter in the old sense and also ether. But it seems to me that until the two, which appear to be so different, are shown to be essentially one, it is better to use the term "matter" strictly in its old sense. But it is advisable to have a term which shall include both matter and ether, and for this place the word "substance" seems suitable.[2] Using the term in this sense, natural philosophy may be defined as the science which treats of energy and substance.

Physics is the science which treats primarily of energy; chemistry is the science which treats primarily of matter. Thus physics considers mainly the actions and transformations of energy through matter and ether; and chemistry considers mainly the actions and transformations of matter through energy. But since energy is manifest to the senses only through matter, and since matter does not exist without manifestations of energy, the relations of the two sciences are very intimate. In any book upon either subject the treatment constantly passes over to the other; indeed, energy and matter are inseparable—one cannot be considered without the other. Recently the relations between physics and chemistry have become even closer by the rise of the intermediate science, physical chemistry. This science completely bridges the gap between the two and unites them as a whole into the conjoint science of physics-chemistry, which is the science of energy and substance. As thus defined, physics-chemistry becomes a synonym of natural philosophy in its broad sense.

---

[1] The principal address given in the Department of Geology of the International Congress of Arts and Science at St. Louis, 1904.

[2] This definition of the word "substance" is different from that of Holman, who, as I understand it, makes the term so comprehensive as to include matter, ether, and energy. By him the word "matter" is apparently used to comprise what is here covered by both matter and ether.—SILAS W. HOLMAN, *Matter, Energy, Force and Work*, pp. 135 ff.

While physics and chemistry are really a single science, it is to be repeated that the chief point of view of physics proper is that of energy, and the chief point of view of chemistry proper is that of matter. This will be appreciated if one but mention the subjects considered in text-books of physics and chemistry. Some of the subjects of physics are sound, heat, light, and electricity. These are all forms of energy. The chief subjects for consideration by chemistry are the elements and their combinations, such as helium, chlorine, iron, calcium carbonate, etc. These are all forms of matter. Since physics-chemistry treats of all the energy and substance within the reach of our senses, physics and chemistry are the two sciences the principles of which are believed to be applicable to the entire visible universe.

Astronomy treats of energy and substance in the heavens. It is concerned primarily with the nature and development of the heavenly systems. Under the above definition, astronomy is the science of the physics and chemistry of the heavens. Biology treats of energy and substance in living organisms. Under this definition, biology is the science of the physics and chemistry of organisms. Geology treats of the energy and substance of the earth. Under this definition, geology is the science of the physics and chemistry of the earth. It includes mineralogy. These definitions may not be complete, but at least they are true so far as they go.

It is not necessary for present purposes, to consider the possible defects of the definitions given, except that for geology. Objections may be raised to defining geology as the science of the physics and chemistry of the earth, on the ground that this definition is inadequate to cover descriptive and historical geology. It may be said that it is a part of geology to describe the facts exhibited by the earth as they appear, without reference to physics or chemistry. It may be said that the history of events, as shown by the rocks and fossils, does not necessarily require physical or chemical treatment. There is some truth in these statements, but on the other side it may be held that the facts are the results accomplished by physical and chemical work. These facts become important and significant mainly as they are interpreted in physical and chemical terms. The objects of the earth—the complex results of chemical and physical work—if described without reference to the manner in which the results came about, have comparatively little interest. In reference to historical geology it may be said that this subject gives a chronological arrangement of the results of chemical and physical work.

It thus appears that physics and chemistry are the elementary sciences, while astronomy, biology, and geology may be defined, possibly with some lack of completeness, as the applications of the principles of physics and chemistry to various complex systems. In this sense astronomy, biology, and geology are applied sciences.

We are now in a position clearly to indicate the relations of geology to the sciences mentioned. So far as the earth is one member of one of the heavenly systems, it is a subject of astronomy. So far as organisms constitute a small part of the earth, they are the subject of geology. Since the earth is one of the subjects of astronomy, and since the entire kingdom of organisms constitutes a small part of the material of the earth, geology is closely related on one side to astronomy, upon the other side to biology. Geology is one of the children of astronomy. Geology begins with the earth at the time of its astronomic birth. As geology is one of the children of astronomy, so biology is one of the children of geology. As the result of various processes upon the earth, chemical and physical, organisms have been formed, and have gone through their long and complex development. But astronomy, geology, and biology—grandparent, parent, and child—have long existed side by side, and their interaction and mutual effects have been most profound. One cannot be comprehended independently of the others.

While geology is very closely related to astronomy and biology, we have seen that it is still more closely related to physics and chemistry. Since physics-chemistry is the science of energy and substance in general, and since geology is the science of the energy and substance of the earth, geology is not simply related to those subjects—it rests upon them as its one secure foundation. They are the elementary sciences upon which geology is based; for they are the sciences of all energy and substance of which the object of geological science is an insignificant fraction.

We have now reached the most fundamental problem of geology—the reduction of the science to order under the principles of physics and chemistry. To a less extent geology is subject to the sciences of astronomy and biology.[1]

While the relations of geology to the other sciences, as above set forth, are incontestible, it was possible to appreciate those relations only after the sciences were well developed. Geology did not begin consciously as the science of the physics and chemistry of the earth. The phenomena of the earth were studied as objects, and thus geology was at first an observational study. The next step, a revolutionary one, was to explain the observed phenomena in terms of physical and chemical processes, many of which could be observed. But few have asked the question: "What is a geological process?"

---

[1] The earth is the vastest aggregate of matter within the direct reach of man. By a study of a small part of this aggregate the principles of physics and chemistry have been formulated. The material which has been studied is but an inappreciable part of the material of the earth, and but an infinitesimal part of the substance of the universe. Yet the doctrine is unhesitatingly accepted that the principles of physics and chemistry, wrought out with reference to this minute fraction of substance, are not only applicable to all the materials of the earth, but to all parts of the visible universe. This daring generalization has received astonishing confirmation by studies of other portions of the visible universe through the spectroscope and photographic plate.

In the generalization that the principles of physics and chemistry, developed by study of small masses of material, apply to all parts of the universe, we have a case of the extension of a generalization from a part to the whole, which surpasses almost any similar extension of reasoning. Indeed, some philosophers have seriously questioned the legitimacy of the conclusion.

In view of the foregoing, it is rather curious that the geologist now finds his most important problem, the problem of problems, in the explanation of phenomena exhibited by the heterogeneous earth in terms of those principles of physics and chemistry built up mainly by observation, experiment, and reasoning upon a minute fraction of the earth.

GEOLOGICAL PROCESSES.

It is a curious fact that, while the word "process" is used in innumerable geological papers and text-books, I have been unable to find anywhere a definition of a "geological process."

I shall define a "geological process" as the action of an agent by the exertion of force involving the expenditure of energy upon some portion of the substance of the earth.

Physical definitions of "force," "work," "energy," and "agent."—In order to understand the above definition of "geological process" it is necessary to define the terms "force," "work," "energy," and "agent."

Hoskins defines "force" as action exerted by one body upon another tending to change the state of motion of the body acted upon.[1] According to Daniell's more simple definition, "force" is any cause of motion.[2]

When a force applied to a body moves the body in the direction toward which the force acts, it does work.[3] In this sense "work" is the product of force into displacement, the common formula being $W = FS$. The unit of work is defined as the quantity of work done by a unit force acting through a unit distance.[4]

Hoskins defines "energy" in the terms of force and work. Thus he says when the condition of a body is such that it can do work against a force or forces that may be applied to it the body is said to possess energy. The unit of energy is the same as that of work.[5] According to Daniell's more simple definition, "energy" is the power of doing work.[6]

The order of definition of the above terms is that in which knowledge of them has developed. The actions of forces in doing work are observed. From such observations the existence of energy is inferred. Wherever forces act upon matter and work is done, energy must exist. Further reasoning shows us that bodies may possess energy which is latent and is not exerting force. Hence many physicists have defined "energy" without introducing the words "force" or "work." Thus, according to Holman, "energy" is power to change the state of motion of a body.[1] If energy be recognized as the primary thing, then "force" can be defined in terms of energy. According to Holman, "force" is that action of energy by which it produces a tendency to change the state of motion of bodies.[2] Similarly, the word "energy" may be introduced into the definition of the word work. Thus Holman says "work" is that action of energy by which it produces motion in a free body, or produces or maintains the motion of a body against resisting forces.[3]

---

[1] T. M. HOSKINS, *Theoretical Mechanics*, 1900, pp. 2 and 16.

[2] ALFRED DANIELL, *A Text-book of the Principles of Physics*, 3d ed. (1895), p. 4.

[3] HOSKINS, *op. cit.*, p. 298.

[4] *Ibid.*, p. 298.

[5] *Ibid.*, p. 308.

[6] DANIELL, *op. cit.*, p. 2.

An "agent" is any portion of the substance of the earth which may exert force and thus expend energy to perform geological work. Thus ether, air, water, and rock are agents.

The next step in the comprehension of geological processes is a consideration of the kinds of energies, forces, and agents, and their relations.

Kinds of energy and force.—Ultimately the forms of energy may be reduced to a few, and possibly to a single kind. Indeed, some physicists believe that all forms of energy are really but different manifestations of kinetic energy. But the number of elementary kinds of energy in the universe is a problem for the physical philosopher, not the geologist. The geologist is concerned in all the kinds of energy which he observes at work. These are: (1) gravitation energy, (2) heat, (3) elasticity energy, (4) cohesion energy, (5) chemical energy, (6) electrical energy, (7) magnetic energy, (8) radiant energy (including radiant heat, radiant light, and electro-magnetic radiation).[4]

From another point of view energy may be classified into kinetic energy and potential energy. Under static conditions of all the parts of a system any or all of the kinds of energy above named may be exerting force, but so long as no motion occurs and no work is done they are all potential. When anywhere in the system movement takes place and work is done, some portion of the energy becomes kinetic. Work and kinetic energy are inseparable. As multifarious kinds of work are always going on in the world, potential and kinetic energy are always existent. For the most part we can trace the kinetic energy back to one or more of the various classes of energy above mentioned, but some part of it may be derived from other unnamed sources.

---

[1] SILAS W. HOLMAN, *Matter, Energy, Force and Work*, 1898, p. 20.

[2] *Ibid.*, p. 41.

[3] *Ibid.*, p. 17.

[4] *Ibid.*, p 37.

Any of the forms of energy may exert force, hence we have the terms "force of gravitation," force of heat," "force of elasticity," "force of cohesion," "chemical force," "electrical force," "magnetic force," and "radiant force."

Any or all of these forces may be exerted both under static and dynamic conditions. When the conditions are static, the energy is potential. When the conditions are dynamic and work is done, some portion of the energy is kinetic. To illustrate: For many years a cliff may stand; but finally a portion of it falls and geological work is done. The force of gravitation is exerting the same pressure upon the material concerned during all the years of quiesence and during the brief period of movement, and for that matter continues to be exerted after movement ceases. During the static conditions the energy of gravitation is potential. During movement some part of it, by pressure of the force of gravitation, passes into kinetic energy. And this energy, through the agency of the falling part, the agent, does further geological work upon the material at the foot of the cliff.

All of the forms of energy and force are important in geology, but the geological work of some of them has been more clearly discriminated than that of others. For instance, the geological results produced by electricity and magnetism have not been worked out, although I have no doubt that electrical and magnetic energy have produced important permanent effects upon the earth which ultimately will be discriminated.

Geological use of the words "force," "energy," and "work."— To the present time the geologist has much more frequently used the word "force" than "energy." This is because the geologist is usually more concerned with the exertion of force by an agent than he is with the source or amount of energy which the agent contains. Physical investigations seem to show that substance contains enormous quantities of energy, only a small part of which is manifest to the senses, and this only under special circumstances. So far as geological bodies have great stores of energy which are not manifest as force, there is no change of condition—no geological process. The geologist is primarily concerned with the energy which is manifesting itself either statically or dynamically by the exertion of force. Consequently, he more often refers to the forces of geology than the energies of geology. This is the more natural since the unit of force and the unit of energy are the same, and that energy is measured only by its action as a force. While in the past the primary interest of the geologist has been in force rather than in energy, it is probable that in the future he will become more and more concerned in the energy itself and its sources.

Often the geologist has made no discrimination between the words "force" and "energy." He has frequently used "force" in the old sense, both to cover the thing itself, the energy, and the action of energy, the force, in accomplishing work. This formerly was the practice of physicists also, who, for instance, spoke both of the conservation of force and the exertion of force. If the conclusion be correct that the source and amount of energy concerned in a process should be discriminated from its action as a force, it is clear that the time has now come when the geologist must in his writing clearly differentiate the two ideas.

Since the physicist now makes an important discrimination between the words "energy" and "force," it may be necessary for the geologist to follow him in his definitions of these words, although much can be said against technicalizing and narrowing the use of the general term "force." Probably the interests of all the sciences would have been best subserved if the physicists had introduced a new word for the technical sense assigned to the word "force," and had left this term to be used in the general way in which it has been used in the past in science, and will continue indefinitely in the future, to be used in literature. This is especially true since, if we confine the word "force" to its physical definition, we are in constant need of a word to cover both energy and force, as defined by the physicists. If the latter word be technicalized, I can think of no better word than "power" for the conception which includes both. This was the word used for this place by Hutton in the opening pages of his epoch-making paper on the "Theory of the Earth."[1]

It is also to be noted that the word "work," as above defined, is also technicalized, having reference only to the exertion of force in producing change of state of motion. With this meaning it has no relation to the material results. To illustrate: By the expenditure of energy, the crust of the earth may be fractured, or material be transported from one place to another. In the general sense used by geologists, these results are often spoken of as "work." It is certainly a very grave question whether geologists can afford to restrict the word "work" to its physical definition, and thus be obliged to discontinue its use in an indefinite sense, both for the expenditure of the energy, and the effect of such expenditure, or for either alone. While this is so, it may be said there are very considerable advantages in having a technical word for the physical meaning of work. This would assist the geologist to think clearly and discriminate between the expenditure of energy and the material effects of such expenditure.

Whatever meaning the geologist assigns to the words "force" and "work," he should have a clear understanding of the conceptions which the physicists have of their meaning, and should attempt to express these conceptions in some way. Also he should make it clear, in case he decides not to use the words "force" and "work" in the physical sense, that the old general usage is retained for them. In this paper I shall use "force" in its technical sense, but retain the common usage for the word "work."

The agents of geology.—We are now ready to classify the agents of geology. They may be grouped into ether, gases, liquids, and solids. Possibly organisms are so peculiar a combination of gases, liquids, and solids that they should constitute a fifth group, and in this case the agents may be classified into ether, gases, liquids, solids, and organisms. From another point of view the agents may be classified into their chemical elements, some seventy or more in number, but of which only about twenty are so abundant as to be important.

The small number of categories of energies and agents given might lead to the conclusion that the subject of geology is reduced to simpler terms than is really the fact. Each of the forms of energy, gravitation, heat, elasticity, cohesion, chemical affinity, electricity, magnetism, and radiation is most complex and acts as forces in most diverse ways. The number of gases, of liquids, and of solids which occur in nature are beyond number. They are most diverse in character. For instance, the liquids vary from nearly pure water to magma. The solids comprise all kinds of minerals, of which there are many hundreds, and the various combinations of these minerals in rocks, the different phases of which are very numerous. Gas without the presence of liquids and solids, liquids without the inclusion of gases and solids, and solids which contain no gases or liquids, while perhaps possible in a physical or chemical laboratory, are not found in nature. As remarked by Powell, gases, liquids, and solids are everywhere commingled upon the earth. All are commingled with ether. Thus the various combinations of agents are beyond computation. Also definite agents, for instance water may occur in various kinds of bodies, each of which acts in a manner peculiar to itself.

---

[1] CHARLES HUTTON, "Theory of the Earth," *Philosophical Transactions of the Royal Society of Edinburgh*, 1785, pp. 212–14.

The materials upon which the agents act are of the same kinds, and have the same diversities and complexities, as the agents themselves. Moreover, the work done inevitably affects both the material acted upon and the agent. The agent that grinds the rock-floor at the bottom of a glacier is also ground. This necessity of work upon both agent and substance acted upon comes under the law of Newton in reference to action and reaction. The fact of work both upon agent and substance upon which the agent acts raises the question as to the distinction between the two. The answer is: The agent is the substance containing energy which it expends in doing work upon other substances. The substance upon which work is done may thereby receive energy, and thus become an agent which does work upon other substances; and so on indefinitely. Indeed, the rule is that one process follows another in the sequence of events, until the energy concerned becomes so dispersed as to be no longer traceable. Theoretically this goes on indefinitely.

Analysis of geological processes.—We have seen that the action of one or more agents through the exertion of force and the expenditure of energy upon one or more substances is a geological process. It is rare indeed, if it ever happens, that a single agent works through a single force upon a single substance. Commonly two or more agents are doing work by the expenditure of energy of various kinds at the same time upon more than one material. The processes of geology, therefore, vary in their complexity from the action of a single agent through a single force upon a single substance, to the action of all kinds of agents through all classes of force upon the most diverse combinations of substances. Thus the solution by rain-water of pure calcite is a process. Also erosion, which is the work of all the agents by the expenditure of various kinds of energy upon the most diverse combinations of materials, is called a process. It is plain that the number of processes of geology, comprising as they do all possible combinations of energies, agents, and substances, are beyond number, if indeed they are not infinite. If geology is to be simplified, the processes must be analyzed and classified in terms of energies, agents, and results. Each of the classes of energy and agent should be taken up, and the different kinds of work done by it discussed. For instance, the work of the force of gravitation through gases, liquids, and solids should be analyzed. To some extent this has been attempted, but very imperfectly indeed. And such discussion has scarcely been seriously undertaken for the other forms of energy. Text-books should consider each of the classes of energy by itself, the nature of the forces it exerts, the processes through which it works, and the results accomplished through the various kinds of agents.

The general work of each of the agents and the results accomplished should be similarly considered. Not only so, but the work of the different forms that each of the agents takes should be separately treated. Thus, besides considering the work of water generally, the work which it does both running and standing must be treated. The first involves the work of streams; the second, the work of lakes and oceans. This involves the treatment of streams as entities, or, to use a figure of Chamberlin's, as "organisms." The treatment of the work of gases should involve the subjects of gases of the atmosphere, gases of the hydrosphere, and gases of the lithosphere. The treatment of the agents will be more satisfactory in proportion as the work done by each of the forms of each of the agents is explained under physical and chemical principles in the terms of energy.

It is plain that the treatment of the energies of geology and the treatment of the agencies of geology will overlap, since one cannot be considered without also considering the other; but this is an advantage rather than a disadvantage, for each of the two points of view is very important in enabling the mind to grasp the composite whole. Just as in the science of physics-chemistry it may sometimes be advantageous to consider the subject mainly from the point of view of substance, and at another time mainly from the point of view of energy, and the treatments from both points of view are necessary to build up the science of physics-chemistry; so it is necessary to consider the subject of geology from the points of view of energy and of agent, if an approximation to adequate comprehension be gained.

As already intimated, another point of view from which geology may be considered is the result. This was the chief point of view of the early geological papers and text-books, which were content to tell of phenomena. Phenomena may, and often are, observed and described in advance of their physical-chemical interpretation. But the naming or even the description of the phenomena of the earth without reference to energy or agent is very unsatisfactory. And usually the valuable descriptions of before unobserved phenomena are made in connection with theories of their physical and chemical significance. But it is still true that observation and description present a third important point of view which interlocks with and overlaps the treatment of geology from the points of view of energy and agent.

So complex is the earth that to enable the mind to comprehend the intricately interlocking whole, the subject should be considered from as many points of view as possible. If only the human mind were sufficiently powerful, and means of expression adequate, the ideal method of treatment would be simultaneous consideration and exposition of all possible points of view. But since this method of treatment is an impossibility, we must necessarily at any time consider each portion of the subject in part and treat it in part. The problem is then the selection of the various partial points of view which are important, and the determination of the order of their consideration.

No one, I think, can hold that any of the points of view above mentioned—process, energy, agent, and result—is unimportant in a general treatment of the subject of geology. It is therefore clear that all these points of view must be handled. There may be difference of opinion as to the order in which they shall be presented; and for different parts of the subject of geology and for different purposes the best order will vary.

We are now in a position to foresee the future development of the science of geology. The early papers and text-books were content to tell of accomplished results. Almost nothing was said with reference to processes. As the science developed, there crept into the literature of the subject more and more reference to processes. The present year a text-book of geology by Chamberlin and Salisbury has appeared, the first which avowedly attempts to treat geology from the point of view of processes rather than phenomena.[1] This is a great step in advance. But a large part of the task of reducing the processes to order in terms of energies, agents, and results still remains to be done. When this is accomplished, we shall have a statement of the principles of geology in terms of physics and chemistry.

How knowledge of processes has developed.—The principles of geology have been developed in the past and will continue to be developed in the future both from the study of processes now in operation and by the consideration of the results of processes which cannot be observed. An excellent illustration of a branch of geology, the principles of which have largely been established by the observation of processes now in operation, is furnished by physiography. So far as one can see, the surface of the land is now being modified by the energies and agents of geology as rapidly as at any time in the past. These energies and agents may have varied in their efficiency from time to time and place to place, but the above statement is broadly true. There are other branches of geology, the principles of which have been mainly developed from results accomplished rather than from observation of the present actions of energies and agents.

---

[1] CHAMBERLIN AND SALISBURY, *Geology*, Vol. I, "Processes and Their Results," 1904.

In such branches the probable energies, agents, and processes which produced the observed results were developed from a consideration of the methods by which chemical and physical energy through the agents available could have produced the results observed. For instance, the development of the solar system occurred but once. During that development the earth was formed, including the atmosphere, hydrosphere, and lithosphere. The process of differentiation was not observed by man, cannot be repeated by him. The only method of reaching a probable conclusion as to the manner of accomplishment of the complex result is to consider in what possible ways physical and chemical energy may have acted upon the enormous masses of universe stuff out of which the earth was constructed, and to check this reasoning by the attainable knowledge of what is now occurring upon other heavenly bodies.

The qualitative and quantitative stages of explanation.—The task of explaining geology in terms of processes involving energy and agent has two stages—the qualitative stage and the quantitative stage. For most problems we have as yet been unable to go beyond the qualitative stage. In the qualitative stage of a problem it is shown that a cause is real. In this stage the question is not asked as to how far the explanation applies; *i. e.*, its quantitative importance. Most geologists are content when they reach the qualitative stage. A certain cause is determined to be real in the explanation of certain phenomena. It is then usually assumed that this cause is the only cause. For instance, it has been generally accepted that the loss of heat by the earth results in decreased volume, and that such condensation is a cause for crustal deformation. Many geologists have stopped at this point satisfied. They have not asked the question: To what extent can loss of heat by the earth explain crustal deformation, and are there any other causes which can be assigned? Some years ago I listed a number of causes, each of which partly explains deformation. In addition to secular cooling, they are as follows: volcanism, cementation, change of oblateness of the earth, change of pressure within the earth, change of physical condition of the material of the earth, and loss of water and gas from the interior.[1]

---

[1] C. R. VAN HISE, "Estimates and Causes of Crustal Shortening," JOURNAL OF GEOLOGY, Vol. VI (1898), pp. 10–64.

Evidently, in order that we may have even an approximately correct idea of the chief causes for crustal deformation, the question must be answered as to the quantitative importance of each of the causes.

The consideration of the processes of geology by quantitative methods is superlatively difficult, yet this task must be undertaken if the science ever approximates certainty of conclusions. This leads to the relations of mathematics to geology. The moment we pass to the quantitative treatment of processes the assistance of mathematics is needed. For simple quantitative calculations arithmetic and algebra may suffice, but for the more difficult problems of geology the assistance of higher mathematics is needed. This, then, raises the question as to whether or not it is expected that the geologist, in addition to knowing physics and chemistry, must also be a mathematician. Undoubtedly this is the ideal equipment of a geologist, which, unfortunately, few if any possess. There are many geologists who apply simple mathematics to various problems. But the man who is so familiar with forces, agents, processes, and phenomena of geology that he is able to handle them, and at the same time is capable of handling higher mathematical reasoning, is rare indeed. Those geologists who have made the attempt to combine mathematical with their geological reasoning usually have shown marked deficiency in their mathematics. Upon the other hand, those mathematicians who have attempted to handle the problems of geology mathematically have usually been so deficient in a knowledge of geology that their work has been of comparatively little value. In view of these unfortunate results, it seems to me that the time has come for co-operation between geologists and mathematicians in the advancement of the science of geology to a quantitative basis. Two or more men should work together, some of them geologists with a broad familiarity with the phenomena and methods of their science, and the others expert mathematicians. In continual consultation, the geologist and mathematician will be able safely to handle the problems of geology quantitatively. This happy condition of co-operation, once reached, will be sure rapidly to advance the science.

The quantitative solution of geological problems is likely to emphasize also another of the principles of geological method of the greatest importance. The causes offered to explain the phenomena do not exclude one another. It is believed that each of them is a real cause, and partly explains the phenomena—that the different causes are complementary. While a majority of geologists have been content with suggesting a single physical cause for a phenomenon, others have taken more than one possible cause into account. Thus Chamberlin[1] has formally adopted the method of multiple hypotheses. But the great majority of those who have considered more than one hypothesis in connection with a geological problem have carried on their discussions as if one of the suggested causes must be selected to the exclusion of the others.

As a matter of fact, almost every complex geological phenomenon has not a simple, but a composite, explanation. To illustrate, in Chamberlin and Salisbury's text-book of geology it is stated that the explanation of volcanism may be given upon the assumption that the lavas are original; or, second, on the assumption that the lavas are secondary. Under the first assumption it is suggested (1) that lava outflows from a molten interior, and (2) that lavas flow from molten reservoirs. Under the second assumption it is suggested that lavas may be assigned (3) to the reaction of water and air penetrating to hot rocks, (4) to relief of pressure, (5) to melting or crushing, (6) to melting by depression, and (7) to the outflow of deep-seated heat.[2] At the close of the discussion it is said that these hypotheses "must be left to work out their own destiny."[3] I fear many will make the inference, although I have no idea that the authors so intended, that one among these hypotheses will be victorious in the struggle for existence and the others totally overthrown. My point in this connection is that the two main suppositions, and all of the hypotheses under them, may be true in part; that these various explanations are not necessarily exclusive of one another, but may be supplementary. When we have a quantitative discussion of the probable effects which may be expected from each of the causes suggested, we shall have some idea of their possible relative importance. For my own part I have no doubt whatever that volcanism is to be explained by some combination of the seven causes mentioned, with doubtless other causes which have not yet been suggested, rather than by a single cause. As soon as it is appreciated that to explain a complex phenomenon several causes are usual, if not invariable, rather than exceptional, it becomes plain that their relative importance should be determined, and this can be done only by quantitative methods.

---

[1] T. C. CHAMBERLIN, "The Method of Multiple Working Hypotheses," JOURNAL OF GEOLOGY, Vol. V (1897), pp. 837–48.

[2] CHAMBERLIN AND SALISBURY, *Geology*, Vol. I, "Processes and Their Results," 1904, pp. 595–602.

[3] *Ibid.*, p. 602.

THE INDIVIDUAL PROBLEMS OF GEOLOGY.

Thus far we have been considering the problem of geology as a general one. The subject assigned, "The Problems of Geology," might imply a treatment of the particular problems at present being considered by geologists. For an address this interpretation of the subject is impracticable. Adequately to discuss one of the unsolved problems of geology from the point of view advocated would require a monograph. Not only is it impossible to discuss unsolved problems of geology, but it is impracticable, within the limits of this paper, even to list the problems demanding solution. As evidence of the correctness of this statement it may be noted that a subcommittee of the Carnegie Institution stated scores of problems upon the investigation of rocks, the statement of which, limited to the briefest possible terms, occupies a number of printed pages.[1]

ILLUSTRATIONS OF TREATMENT OF GEOLOGICAL PROBLEMS FROM THE POINT OF VIEW OF ENERGY, AGENT, AND PROCESS.

While it is not practicable to discuss, or even to list, the particular problems of geology, it is possible to mention illustrations of the systematization and simplification of the science by the treatment of processes in terms of energy and agent. These I shall take from my own publications, for the reason that I can more easily give them than any others. My chief subjects of study have been (1) the gross and minor deformations of the lithosphere, and (2) the interior transformations of the rocks, or metamorphism. When I began the study of the first of these subjects, I found a heterogeneous mass of facts in reference to the deformation of many regions, with various guesses as to how the results came about, but with no consistent attempt to reduce the many observed phenomena to order under the principles of physics and chemistry. The subject of metamorphism was in an even worse condition. The work upon this subject was of the most random character; indeed, nothing short of chaos prevailed. A person who attempted to carry the multitudinous statements of facts in his mind would need more than cyclopedic powers of memory, and the statements would not even have had the artificial order of an encyclopedia. I became convinced that, if the treatment of metamorphism was to continue along the old lines, the subject was doomed to hopeless confusion.

---

[1] *Carnegie Institution Year-Book*, No. 2, pp. 195–201.

With the above condition of affairs before me, I set about attempting to ascertain the principles which control the various kinds of deformation of rock masses, and which underlay the transformation of rocks. It soon became plain to me that the task was a great problem in applied physics and chemistry. When this was realized, it became clear that it was necessary to know the principles of physics applicable to the deformation of matter and to the alteration of rocks. Thus my first task was to remedy the defects of my basal training by gaining a working knowledge of the well-established principles of these subjects. This task I found a formidable one, which occupied much of my time for several years, and which I can claim to have only very imperfectly accomplished.

In order to understand the diverse phenomena of crustal deformation, it was plainly necessary to know the principles of deformation of small masses, such as can be handled in the laboratory. Unfortunately it was found that this part of the subject of physics is in a very imperfect condition. No systematic statement is available as to the manner in which different substances behave under varying conditions of stress. While studies have been made of the deformation of iron under a moderate range of conditions, comparatively little has been done concerning brittle bodies such as constitute the rocks. Exact knowledge is needed as to the behavior of rocks under the most extreme variations of stress, temperature, amount of water, and other conditions. But while it is highly desirable to have this knowledge, the geologist cannot wait until it is available. The only practicable course is to study closely the phenomena of rock deformation, and interpret these facts in the light of the physical and chemical knowledge available.

A broad study of the phenomena of deformation by various men showed two classes of very diverse phenomena. In some areas the prominent deformations of the rocks are those of fractures, such as joints, faults, brecciations, etc. In other places the deformations are mainly those of flexure. For instance, in some places one finds that brittle rocks, such as jaspilite and quartzite, are deformed almost wholly by numerous fractures, and in other places have been bent within their own radius, or even minutely and extremely crenulated with no sign of fracture. A close study of the geological conditions under which these two classes of deformation occurred shows that the more modern rocks, which have at no time been very deeply buried, are those which are most likely to exhibit only the effects of rupture; whereas the ancient rocks, and especially those which have been deeply buried, are likely to show the evidence of profound folding without rupture, although often there is superimposed upon the flexures more recent fracture deformation. Physical experiments had shown that, when a brittle substance like a rock is stressed beyond the limit of elasticity under the conditions of the earth's surface, that cohesion is overcome, and rupture takes place. This fact, correlated with the general observation of rupture in recent rocks and those deformed near the surface, led to the conclusion that normally the deformation of the outer part of the earth is by fracture.

After this conclusion was reached, it was a natural step to the conclusion that at a very moderate depth below the surface of the earth the superincumbent pressure is greater than the strength of any rock, and that, if openings could be supposed to exist, they would be closed by pressure; in other words, that the pressure due to the force of gravitation is sufficiently great so that the molecules of the rocks are held within the limits of molecular attraction or are within the limits of the force of cohesion. This naturally led to the suggestion of a deep-seated zone of rock-flowage, in opposition to a zone near the surface, that of fracture. At the time this conclusion was reached, no experiments had been made actually showing the deformation of rocks under the conditions of the deep-seated zone, but since that time Adams and Nicolson have deformed rocks by flowage in the laboratory.[1] Thus observation of the geologist, inference from the observation, and experimental work have led to advance in the science of physics.

For the present purpose the important thing is to observe that a realization of the very diverse results which follow from deformation under different physical conditions led to a satisfactory classification of two great sets of phenomena which had been noted, but without any reason being assigned why one occurs at one place and the second at another place. Thus in the text-books of geology joints, faults, and folds were described. But there was no attempt to explain why fracture occurred here, folds there, and in a third place both. After it was realized that the great earth-movement makes joints, faults, and other fractures at and near the surface, and at depth, below these structures, other structures which have been called folds, it was possible to reduce the gross deformation of rocks to some systematic order under the principles of physics. There of course remains the working out of the precise physical conditions which result in the various diverse phenomena. For instance, what are the exact conditions of stress which result in the many complex systems of joints? While progress has been made upon this and other problems of gross deformation, a vast amount of work remains to be done before the subject will be even approximately reduced to order in the terms of energy, agent, and process.

It has already been intimated that the subject of rock alteration was in an even more unsatisfactory state than that of gross deformation. The particular alteration of this or that rock was given without any adequate consideration of the geological, physical, or chemical conditions under which the change took place. Thus there were many thousands of descriptions of rock alterations, but no understanding of the reasons why the particular alteration for a given rock found at a given place occurred. To make the matter worse, almost every description of rock alteration was accompanied by vague guesses as to the causes of the changes, the majority of which were little short of grotesque.

---

[1] F. D. ADAMS AND J. T. NICOLSON, "An Experimental Investigation into the Flow of Marble," *Philosophical Transactions of the Royal Society of London*, Series A, Vol. CXCV (1901), pp. 363–401.

After it was appreciated that the gross deformation of rocks is very different in an upper and a deeper zone, the question naturally arose as to whether there are not differences in the rock alterations in these zones. This idea, when followed up, resulted in astonishingly fruitful results. It was found that in the upper zone, that of fracture, the chief alterations which take place are those of oxidation, carbonation, and hydration. These reactions occur with liberation of heat and expansion of volume. In other words, the reactions are controlled by chemical energy. In the lower zone the dominant factor controlling alterations is physical energy. Pressure diminishes the volume. In order to accomplish this, the chemical reactions of the upper zone are reversed. Deoxidation, silication with decarbonation, and dehydration occur with absorption of heat. The reactions controlled by the force of gravitation are under the principles of physics. It thus appears that the reactions of the two zones are opposed throughout. It is plain that if the subject of metamorphism is to be reduced to order, the alteration of the upper zone, that of fracture, must be discriminated from that of the deep-seated zone, that of rock-flowage.[1]

The working out of the principles of metamorphism was a physical-chemical problem. The handling of the problems of rock alteration with fairly satisfactory results was possible because of the rise of physical-chemistry. Had this science not been developed within the past score of years, it would not have been possible to have gone far upon the problem of metamorphism.

It is to be emphasized that gross deformation is not independent of metamorphism, or metamorphism independent of gross deformation; the two interlock. The general solution of the problem of gross deformation made it possible to formulate the principles controlling the interior transformations of rocks. In a similar manner these problems interlock with the other problems of physical geology, and physical geology interlocks with the other sides of the subject. The whole science is one interlocking system, a part of which cannot be satisfactorily developed independently of the other parts. For instance, weathering can be placed in order only when considered in connection with general metamorphism, erosion, and sedimentation. Ore deposits can be explained only by combining the principles of volcanism, deformation, metamorphism, etc.

---

[1] The necessarily narrow limits of this paper render it extremely difficult to show the manner in which the subject of metamorphism has been treated under the system advocated as a general method for geology. By referring to *Monograph XLVII of the United States Geological Survey,* a treatise on metamorphism now just appearing, the reader will better appreciate the illustration. In this volume the forces of metamorphism, the agents of metamorphism, and the zones of metamorphism, are first fully treated, the point of view being mainly physical-chemical. After the general principles contained in these chapters are given, the alterations in each of the different belts and zones are developed. The point of view of the latter chapters is mainly geological, but the geology is interpreted in the terms of the principles earlier formulated.

In attempting to reduce a small part of the subject of geology to order under the principles of physics and chemistry, the plan was followed of oscillating between observations of the facts as exhibited in the field and laboratory, and their physical-chemical explanation. After a large number of facts were observed in the light of known principles, the attempt was made better to formulate the principles which explain them. After this was done, the facts were again more comprehensively studied in the field and in the laboratory in the light of the new principles. The statement of principles was then modified and improved by use of the new facts. The improved statement of principles was again tested by further facts. Thus the process of development has been a series of approximations toward both completeness of statement of fact and perfection of formulation of principle, but neither have been attained, nor, so far as we can see, will they ever be reached.

NECESSITY FOR ADVANCE IN THE SCIENCES OF PHYSICS AND CHEMISTRY.

Very often, in the attempt to find principles applicable to the phenomena of deformation and metamorphism, it has been found that the science of physics-chemistry is not sufficiently advanced to make this possible. In such cases physicists and chemists have been asked to develop this subject at the needed points. But at innumerble places the problems have proved to be so numerous and complex that the necessary aid has not been obtainable. Thus there has arisen, with reference to my own work, a great line of unsolved problems which demand the co-operation of physicists and chemists. The same is true of the work of all other geologists interested in the fundamental problems of geology. As a consequence, when a committee was appointed by the Carnegie Institution to consider what could best be done for the advancement of geology, it was unanimously decided that the most pressing need of the science was, not further support of the study of the phenomena of geology, but the advancement of the principles of physics and chemistry upon which geology is based.[1] In a small way some of the physical and chemical problems, the solution of which are asked by geologists, have been taken up by the Carnegie Institution. Thus the demands of the geologists that their science shall be reduced to order under the principles of physics and chemistry are likely to result in important advances of these sciences.

DEFECTS OF GEOLOGICAL LITERATURE.

If further proof than that already given were needed of the importance of the knowledge by geologists of the basal principles of the elementary sciences, and of their application to geological problems, it is furnished by the literature of geology. It seems to me that the radical defect which pervades the literature of the subject is due to the lack by geologists of such knowledge. Because of this, many geologists are wholly unable to make a logical arrangement of their material, or respectably to discuss the phenomena observed with reference to causes.

Indeed, some geologists seem to take pride in lack of knowledge of principles and of their failure to explain the facts observed in the terms of the elementary sciences. I have heard a man say: "I observe the facts as I find them, unprejudiced by any theory." I regard this statement as not only condemning the work of the man, but the position as an impossible one. No man has ever stated more than a small part of the facts with reference to any area. The geologist must select the facts which he regards of sufficient note to record and describe. But such selection implies theories of their importance and significance. In a given case the problem is therefore reduced to selecting the facts for record, with a broad and deep comprehension of the principles involved, a definite understanding of the rules of the game, an appreciation of what is probable and what is not probable; or else making mere random observations. All agree that the latter alternative is worse than useless, and therefore the only training which can make a geologist safe, even in his observations, is to equip him with such a knowledge of the principles concerned as will make his observations of value.

---

[1] *Carnegie Institution Year-Book*, No. 1, 1902, No. 2, 1903.

It is doubtful if more than one or two text-books of geology have been written which do not contain many statements capable of arousing the amusement of the physicist. When the geologists who write the standard books of the science are properly equipped with a working knowledge of the principles of physics and chemistry, the books will cease to be a heterogeneous mass of undigested material mingled with inferences as to the meaning of the phenomena, which to anyone familiar with the principles of physics and chemistry are often ludicrous. From the above point of view, it might be said that the problem of geology, the problem of problems, is to get men who write geological papers and books so well trained in the elements of the sciences upon which geology is based that they shall be able to reason correctly as to physical and chemical causes, and consequently to observe and describe accurately and discriminatingly. It is plain that the geologist who hopes to advance the principles of his science must have a working knowledge of physics and chemistry.[1]

PRINCIPLES OF GEOLOGY THE SAME FOR THE ENTIRE EARTH.

The phenomena of geology for any extensive area—for instance, a continent—are so numerous that, had the science originated in Europe, in America, and in Asia independently, the principles of the science developed in these three regions would have been essentially the same. The chief differences would have been that the emphasis placed upon the different principles would have varied. Also the principles of certain divisions of the subject would have been somewhat more fully developed in one case than in another. For instance, because of differences in the range of latitude and other climatic conditions, certain parts of the principles of physiography would have been more fully developed on one continent than in another.

It is, of course, understood that the foregoing statements premise that men of equal ability and attainments had been at work on the problems of geology in the various continents. This supposition is, of course, erroneous, for it is evident that the great constructive work of geology has been done largely by a comparatively few individuals. Indeed, the contrast between nations in the number of creative geologists which they have produced is so great that it is a fair inference that the differences in the principles of the science developed in the three continents under the conditions named would have been more largely due to difference in the capacity of the geologists than to variation in the phenomena demanding explanation. In geology, as in other lines of human endeavor, the exceptional man, the genius, is a factor of paramount importance.

---

[1] C. R. VAN HISE, "Training and Work of a Geologist," *Proceedings of the American Academy of Sciences*, Vol. LI (1902), pp. 399–420.

THE PROBLEMS OF PROVINCES AND DISTRICTS.

Thus far we have considered only the development of the principles of geology. They are applicable to the entire earth. There is another great field of geology, which has not yet been suggested—the application of the principles to provinces and districts.

This second line of problems of geology is illustrated by such subjects as the stratigraphy of a given district, its physiography, its paleontology, etc. The working out of the stratigraphy, or physiography, of a given county or township may be of great importance to the inhabitants of that county or township, or even of some consequence to the nation. They are, however, of much less importance to persons interested in the advancement of the principles of geology, unless their elucidation adds to the science some new principle, or some unusually fine illustration of an old principle.

The principles of geology may be broadly comprehended by a single individual. No individual can be familiar with more than a minute fraction of the applications of the principles to the numerous geological provinces of the world. Scarcely a score of years ago it was possible for a geologist not only to know the developed principles of the science, but to know somewhat fully the facts upon which those principles were based. At the present time this is impossible. A man may know the more important facts in reference to a few districts, the broader facts in reference to states, and some of the more general facts in reference to an entire continent, or even more than one continent; but no man can know more than an inappreciable portion of the geological facts of even the countries which have been somewhat closely studied; and these countries comprise but a small part of the earth.

But it is unnecessary for a man to know all the facts of geology. He need only know the more important facts for a sufficiently broad region so that he may understand the recognized principles of the science, assist in their development, and take part in the discovery of new principles. The discoveries will be found to be largely applicable to the vastly greater regions of the world which are not considered by the discoverer. All this is very fortunate for the science of geology. A student beginning the subject may fully comprehend the truthfulness of many principles which have been developed in various parts of the world through the illustrations furnished by his native parish.

From the foregoing it appears that the geology of the future is to have two aspects, which, as time goes on, will become more and more clearly differentiated: first, the principles of geology; second, the application of principles to various parts of the world.

CONCLUSION.

It is clear that the evolution of the science of geology has followed a strictly natural course. Before the subject was recognized as a science, the earth was being observed. When man turned to nature-study, he began to observe the phenomena exhibited by the earth, such as the stratification of the rocks, and the presence in them of objects which are called fossils. After such observations were made, it was inevitable that sooner or later the question should arise as to the manner in which the results observed were accomplished. Thus the observation of phenomena led to a study of processes. Sands like those observed in a consolidated form were seen in the process of building. The conclusion followed that the consolidated stratified rocks were formed by the processes observed upon the seashore. Sea shells were seen to be produced by animals and to be deposited with the upbuilding sands. This led to the explanation that the fossils in the sedimentary rocks were due to the processes observed.

After a large number of explanations, the methods of which were the same as in the illustrations given, the general doctrine was evolved that the geological results of the past are to be explained by present processes, or the present is the key to the past. While the above conclusions now seem almost axiomatic, we need not go far back to find them astonishing novelties. So far as we are aware, the natural explanation of fossils was first reached by that amazingly versatile genius, Leonardo da Vinci, in the fifteenth century. The conclusion that the present is the key to the past required for its formulation the intellect of the great Hutton.[1] It was not announced until 1785, and the doctrine was not generally accepted until after Lyell's *Principles* appeared in 1830.

As the science of geology developed, the practice of explaining the phenomena in terms of processes gradually became more common, until, as we have seen, it is dominant in the latest geological text-book. But, as already intimated, the analysis of processes in terms of energy, force, and agent has only begun. It is my belief that at some time in the future a text-book of geology will appear which begins with a discussion of the energies, forces, and agents of geology, the understanding of which is necessary in order adequately to comprehend processes. It has been stated that the problem of geology is the reduction of the science to order under the principles of physics and chemistry. This is equivalent to saying that the problem of geology is the discussion of the subject in terms of energies, forces, agents, processes, and results. Such a discussion will constitute the principles of geology.

It is my deep-seated conviction that by the solution of this problem only can geology be so simplified as to be comprehended with reasonable fulness by the human mind. When this work is done, the broad principles of the science will be capable of statement with comparative simplicity and brevity. But so broad and complex is the science of geology that a comprehensive statement of the principles of the entire subject will necessarily be somewhat voluminous.

---

[1] How clearly the great Hutton appreciated the doctrine commonly called that of uniformity is shown by the following quotations from his "Theory of the Earth": "In what follows, therefore, we are to examine the construction of the present earth, in order to understand the natural operations of time past; to acquire principles, by which we may conclude with regard to the future course of things, or judge of those operations, by which a world, so wisely ordered goes into decay; and to learn by what means such a decayed world may be renovated, or the waste of habitable land upon the globe repaired." The concluding sentence of his work is: "The result, therefore, of our present inquiry is, that we find no vestige of a beginning—no prospect of an end."—CHARLES HUTTON, "Theory of the Earth," *Philosophical Transactions of the Royal Society of Edinburgh*, 1785, p. 218; *ibid.*, p. 304.

Supplementary to the principles of geology, which are applicable to the entire earth, there will be a long series of volumes of the geology of different continents, the various political divisions of these continents, the states under those divisions, or even the minor areas, such as counties or townships; for so numerous are the facts of the science that it requires a volume to discuss in detail even a small area. For instance, to give the geology of a township with sufficient fulness to make clear the earth-story there illustrated may require a good-sized volume.

We have seen that geology rests upon physics and chemistry as its foundation; that it is closely related upon one side to astronomy, upon another side to botany; that in its broader sense it includes mineralogy; and that for its satisfactory development the aid of the higher mathematics is needed. It is evident that the man who is to advance geology must be broadly trained in science, and that he have a firm grip upon the nature of energy, ether, and matter, and their interactions.

It is my conviction that when geology is placed in order under the principles of physics and chemistry the science will have passed through a greater revolution than at any previous time in its history.

CHARLES R. VAN HISE.

UNIVERSITY OF WISCONSIN.